GOLDER

TECHNICAL MEMORANDUM

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SUPPLEMENTARY LAKE GERALDINE WATER BALANCE MODELLING

1.0 INTRODUCTION

This technical memorandum has been prepared by Golder Associates Limited (Golder) for Colliers Project Leaders (Colliers) on behalf of the City of Iqaluit (the City) to provide additional water supply forecasting estimates to an earlier water balance report prepared by Golder in 2013. In order to minimise the risk of misinterpretation, the information presented in this technical memorandum should be read and interpreted in conjunction with Golder (2013).

1.1 Background

The City of Iqaluit depends on the Lake Geraldine reservoir for its year-round municipal water supply. Given that the reservoir is frozen over for approximately eight months of the year, raw water supplies at the end of summer need to be sufficient to service the City over the following winter until snowmelt runoff replenishes the reservoir during the next spring melt period.

The City has commissioned a number of studies in recent years which suggest that the existing reservoir will not be able to supply sufficient water over the long term to meet growing demands. A number of supplementary water supply alternatives were investigated by Trow in 2004 leading to recommendations to (i) increase the storage capacity of the reservoir and (ii) identify a suitable supplementation source that may be used to augment water supplies during the ice-free period on a needs-must basis.

The height of the Lake Geraldine reservoir was subsequently increased by two meters in 2006, however, it is understood that regulatory limits for water takings from the nearby Apex River have prevented the implementation of a suitable water supply supplementation system at this time. Based on recent communications with Colliers (2018), it is Golder's understanding that recently measured reservoir levels may be insufficient for the coming winter without implementing appropriate water conservation and/or supplementation measures.

1.2 Objectives

The purpose of this technical memorandum is to provide additional water supply forecasting estimates that may be used by Colliers to identify a suitable water supply solution for the coming winter. To this end, Colliers have specifically requested that Golder address the following meteorological uncertainties:

1) The amount of precipitation required to replenish the reservoir from 109.6 masl to as close as possible to its design level of 111.3 masl at various consumption rates identified later in this document;

2) The amount of precipitation can be expected during the remaining ice-free period and to what elevation would this fill the reservoir; and

3) The average precipitation amounts for Iqaluit, on a month by month basis.

In addressing these uncertainties, it is noted that the limiting effects of evapotranspiration and soil and depression storage mean that only a portion of precipitation within the Lake Geraldine catchment (referred to as meteorological surplus) will translate into recharge of the reservoir. For ease of interpretation, this technical memorandum thus presents corresponding estimates for both precipitation and surplus.

2.0 METHODOLOGY

The methods employed for this investigation are generally consistent with, and limited by previous assumptions incorporated into, the approach documented in Golder (2013). A brief summary of the 2013 approach, and a detailed inventory of any modifications to this approach, is provided below for context.

2.1 Consistencies with the 2013 Modelling Approach

As noted previously, the methods employed for this investigation are largely premised on, and consistent with, the model setup developed in 2013. Specifically, consistencies with the previous approach include:

2.1.1 Catchment and Basin Physiography

The physiographic representation of the contributing catchment and reservoir basin within the model have remained unchanged since 2013. Specifically, this maintains consistency with the approach used to characterise the surficial geology, topography and size of the drainage catchment as well as Lake Geraldine's bathymetry and stage-storage relationship.

2.1.2 Water Level Control and Intake Infrastructure

All basin inputs generated by measured meteorological inputs and water supplies accumulated within the reservoir are constrained by the same spillway and intake configuration developed in the 2013 model.

As such, any inputs beyond the reservoir's 1,875,526 m^3 storage capacity are assumed to be lost from the system. Similarly, any water below the assumed intake invert of 101.6 masl is assumed to be inaccessible for municipal use.

2.1.3 Ice Storage

All ice formed within the reservoir is assumed to be inaccessible, and commensurately diminishes available water supplies, until the following spring freshet.

2.1.4 Water Balance Formulation

The calculation of basin yields and reservoir supplies is identical to that detailed in Golder (2013).

Catchment yield, or surplus, is calculated as follows:

(Rainfall + Snowmelt) - (Evapotranspiration + Sublimation) – Change in Available Soil Storage = Surplus (Runoff)

2.1.5 Model Calibration and Validation

No calibration or validation simulations were carried out as part of this investigation. As such the model is limited by the performance metrics generated from available observational data in 2013 and no further observational comparisons have been made to verify model performance.

2.2 Updates to the 2013 Modelling Approach

The following subsection documents changes made to the 2013 water balance model in order to accommodate the particulars of this scope of work.

2.2.1 Water Consumption and Intake Withdrawal Rates

Golder (2013) previously presented a range of daily consumption rates in order to elucidate the effects of population growth or reduction on the long-term sustainability of water supplies in the Lake Geraldine reservoir. The water balance investigation presented herein instead considers three different consumption rates provided by Colliers for specific examination, including:

- No Water Consumption Scenario - 0 m^3/day;
- 100,000 m^3/month Water Consumption Scenario - 3,335 m^3/day; and
- 115,000 m^3/month Water Consumption Scenario - 3,850 m^3/day.

2.2.2 Meteorology

Meteorological inputs in the 2013 version of the water balance model were predominantly based on data measured at Iqaluit A (Station ID: 2402590), supplemented with data from Iqaluit UA (Station ID: 2402594), Iqaluit Climate (Station ID: 2402592) and Iqaluit AWOS (Climate ID: 2402591) resulting in 49 years of data ranging between 1957 and 2009.

The latest assessment considers only the ten most recent complete years of data (2008 through 2017) predominantly obtained for Iqaluit Climate (Station ID: 2402592) and supplemented with data from the four overlapping years (2008 through 2011) of the 2013 data and Iqaluit A (Station ID: 2402590). Because all stations are all in relatively close proximity to one another (500 m) and installed at relatively consistent elevations (29.5 masl to 33.5 masl), orographic, rain shadow and other variances are expected to be negligible at the scale of the ten-year period considered.

A few minor remaining data gaps of a few days or less were identified for wind speed and relative humidity (both used in the determination of potential evapotranspiration estimates) precipitation and air temperature. To develop a complete meteorological record for the water balance model, these data gaps were filled using simple linear interpolation.

2.2.3 Water Level Initial Condition

The 2013 water balance model was initiated in warm-up mode, meaning that a few years of meteorological influences were simulated until dynamic equilibrium had been achieved before production simulations were carried out. This approach allowed water balance variations to occur both in response to concurrent meteorological influences but also as a consequence of water balance deficits or surpluses in previous years.

Because this investigation is focused on shorter-term water level responses to summer precipitation surplus, model setup was slightly modified to facilitate a water level ‘reset condition’ on July 17th of every simulation year to trigger a 109.6 masl initial water level condition to match the most recent reservoir level measurement collected at noon on July 17, 2018.

3.0 ASSUMPTIONS AND LIMITATIONS

The analyses, results and discussion included in this technical memorandum are presented in good faith and limited by a number of assumptions, including:

- Assumptions and Limitations presented in Golder 2013 and the covering email proposal entitled Supplementary Lake Geraldine Water Balance Modelling Assessment submitted to Colliers Project Leaders by Golder Associates Ltd. on July 17, 2018 at 11:51 am;
- For the purposes of simulating evapotranspiration losses from Lake Geraldine's water surface, the model assumes a surface area equivalent to the maximum design elevation of the reservoir. This is conservative because evapotranspiration losses will typically be lower given the reduced surface area of the reservoir at lower elevations;
- The predicted water supply deficit is estimated as the difference between the maximum capacity of Lake Geraldine at the spillway elevation and the available volume of water at the predicted freeze-up date of each simulation year;
- Available reservoir volumes are independent of the effects of antecedent weather conditions or consumption losses and are initialised based on a measured July 17 water level of for each year;
- Estimates of necessary precipitation and meteorological surpluses are represented as percentage increases of rainfall during historically recorded rainfall days; accordingly no increase in the number of rainfall days has been allowed for in the modelling;
- The probability distributions of historic and predicted meteorological conditions are calculated as independent variables as later explained in Section 4;
- Freeze up is identified as the earliest day, following the summer season, when the preceding 14 average is lower than -1°C, in order to prevent false identification of the freeze-up day, a secondary condition is imposed, requiring that the maximum temperature in the period corresponding with 14 to 28 day prior to the freeze-up date, to be larger than 2°C.

4.0 RESULTS

The results presented throughout Sections 4.1 through 4.3 often concern independently calculated probability distributions of historic (2008 through 2017) meteorological data which are intended to confer an understanding of the range of meteorological variability affecting water surplus outcomes for each of the consumption scenarios discussed in Section 2.2.1.

As such, it is important that the reader understand that the percentage probability distributions presented for precipitation and meteorological surplus in Tables 2, 3, 4, 6, 8 and 10 are considered as independent distributions and should not be considered as co-dependent to one another. For example, the 50 percent probability surplus for August presented in any of these tables does not necessarily correspond to the 50 percent probability value for the open-water period. Similarly, the 75 percent probability value for meteorological surplus does not necessarily result from the 75 percent probability value for precipitation.

To assist the reader, bracketed monthly values that are normalised against open-water period totals are included in some data columns.

4.1 Historic Precipitation, Predicted Surplus and Predicted Reservoir Level at Freeze-Up

After applying the gap-filled meteorology data (Section 2.2.2) and water level reset function (Section 2.2.3) to the model, simulations were carried out for the three water consumption scenarios identified in Section 2.2.1 to ascertain the quantity of surplus that would be delivered to the Lake Geraldine Reservoir between July 17 and freeze-up of each year.

Table 1 provides a simplified presentation of key periods of interest requested by Colliers (2018) for the 2008 through 2017 meteorological window considered in this assessment. This information is presented with a view of providing baseline information against subsequent precipitation and meteorological surplus increases presented in Tables 5, 7 and 9.

As shown, a significant portion of total precipitation over the catchment is lost in the form of evapotranspiration either directly from ground surface or more indirectly from soil and depression storage within the catchment. With cooling air temperatures and reasonable precipitation amounts, the proportion of rainfall translated to surplus is shown to generally peak in September. Although higher precipitation is typically observed in August, the amount of generated surplus is likely limited because of increased thermal exposure at ground surface (i.e., increased losses in the form of evaporation). Meanwhile, although lower average temperatures occur in October than September, it is likely that a more significant portion of October rainfall is intercepted within soil storage and ground depressions, thus diminishing catchment runoff to the reservoir.

Total meteorological surpluses in the final weeks (October) before freeze-up are limited relative to earlier portions of the open-water period and thus reduce the catchments capacity to fully replenish the reservoir before freeze-up occurs.

Table 1: Average (Arithmetic) Precipitation and Meteorological Surplus recorded for Iqaluit over the 2008 through 2017 Period

Period	Precipitation (mm)	Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
July 17 to Freeze-Up (Varies)[1]	156	99	63%
July 17 through 31	38	22	58%
August	56	31	55%
September	50	38	76%
October 1 to Freeze-Up (Varies)[1]	11	7	64%

Period	Precipitation (mm)	Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
November 1 to Freeze-Up (Varies) [1,2]	1	0	n/a[2]

Notes:
1. Effective length of ice-free period (i.e., the number of days since July 17 to estimated freeze up day) differs between years.
2. Rounding errors over a short period in 2010 render a comparison of precipitation and meteorological surplus meaningless.

4.1.1 Predicted Precipitation, Surplus and Reservoir Level under No Water Consumption Scenario

Table 2 presents precipitation amounts and corresponding meteorological surplus between July 17 and freeze-up for a range of percentage probabilities over the considered ten year period between 2008 and 2017. Depending on the wind and air temperature magnitudes as well as intensity and distribution of rainfall, the meteorological surplus could represent between 37% and 78% of total precipitation over the Lake Geraldine catchment.

Based on the meteorological data considered, it is estimated that the median water supply deficit without any consumption would approximate 245,000 cubic metres. It is noted that depending on the extreme annual water balances over the same period, there is a possibility that the reservoir deficit at the predicted freeze-up date would range from approximately 7,000 cubic metres to approximately 408,000 cubic metres.

Golder (2013) has previously inferred a relationship between winter length and the quantity of reservoir water that is converted to ice. Based on this relationship, an average winter length of 8 months was shown to lock up as much as 505,000 m^3 of reservoir water (unavailable until melt) and a longer winter duration of 9 months could lock up as much as 585,000 m^3 of reservoir water. For the purposes of evaluating water supply deficits in a conservative manner, a 9 month winter and equivalent ice storage was selected for this assessment.

Given that up to 585,000 cubic metres of active (accessible) reservoir storage (circa 1,875,500 m^3) may be converted to ice during the winter months (Golder 2013), the total available surplus for the over-winter period would range between 883,000 m^3 and 1,284,000 m^3.

Table 2: Precipitation and Predicted Catchment Surplus for 2008 through 2017 Period Under No Water Consumption Scenario

Percentage Probability of Exceedance	Predicted Freeze-Up Date	Number of Open-Water Days from July 17 to Freeze Up	Number of Rainfall Days from July 17 to Freeze-Up	Historic Precipitation (mm)			Predicted Historic Surplus (mm)			Predicted Reservoir Deficit at Freeze-Up (m^3)	Predicted Available Water Supply at Freeze-Up (m^3) [4]	Predicted Reservoir Level at Freeze-Up (masl)
				Open Water Period	August	September	Open Water Period	August	September			
0 (Max)	06-Nov	112	74	283	93 (70)	92 (70)	222	60 (42)	79 (56)	6,679	1,283,847	111.30
5	02-Nov	109	72	248	84 (67)	92 (73)	190	54 (41)	78 (59)	7,116	1,283,410	111.30
10	30-Oct	106	70	213	74 (64)	92 (79)	158	48 (40)	78 (65)	7,554	1,282,972	111.30
25	16-Oct	91	65	184	63 (66)	58 (60)	128	44 (49)	45 (51)	84,842	1,205,684	111.05
50	14-Oct	89	50	147	58 (61)	45 (48)	83	33 (35)	34 (37)	245,100	1,045,426	110.53
75	10-Oct	85	41	108	47 (49)	34 (36)	56	18 (23)	24 (30)	333,950	956,576	110.24
90	05-Oct	80	35	95	32 (46)	24 (34)	39	7 (14)	13 (24)	363,128	927,398	110.14
95	04-Oct	79	32	95	31 (46)	22 (33)	37	4 (11)	11 (26)	385,484	905,042	110.07
100 (Min)	03-Oct	78	29	94	30 (30)	20 (20)	35	1 (1)	8 (8)	407,840	882,686	109.99

Notes:
1. Unbracketed precipitation and surplus values are based on independent probability distributions for examined month.
2. Bracketed monthly precipitation and surplus values are normalised based on total precipitation or surplus for the Open Water Period July 17 to Freeze-up.
3. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.
4. Predicted Available Water Supply at Freeze-Up calculated by removing 9 months of ice storage (585,000 m^3), reservoir deficit (tabulated) and dead storage (80,667 m^3) from total reservoir storage capacity (1,956,193 m^3).

4.1.2 Predicted Precipitation, Surplus and Reservoir Level under 100,000 m^3/Month Water Consumption Scenario

Table 3 considers the same meteorological data discussed for Table 2, but accounts for the additional effects of a daily water consumption rate of 3,335 m^3 (or 100,000 m^3 per month).

Based on the ten year meteorological period considered, it is estimated that the median water supply deficit at a consumption rate of 100,000 m^3 would approximate 522,000 cubic metres. At the extreme ends of the annual water balances for the same period, there is a possibility that this water supply deficit could decrease, or increase, to 64,000 or 698,000 cubic metres, respectively.

Golder (2013) has previously inferred a relationship between winter length and the quantity of reservoir water that is converted to ice. Based on this relationship, an average winter length of 8 months was shown to lock up as much as 505,000 m^3 of reservoir water (unavailable until melt) and a longer winter duration of 9 months could lock up as much as 585,000 m^3 of reservoir water. For the purposes of evaluating water supply deficits in a conservative manner, a 9 month winter and equivalent ice storage was selected for this assessment.

Given that up to 585,000 cubic metres of active (accessible) reservoir storage (circa 1,875,500 m^3) may be converted to ice during the winter months (Golder 2013) and assuming an average winter length of 9 months, a 100,000 m^3/month water consumption rate could potentially lead to over-winter water shortages for the 25 through 100 percent probability outcomes presented in Table 3.

Table 3: Precipitation and Predicted Catchment Surplus for 2008 through 2017 Period Under 100,000 m³/month Water Consumption Scenario (3,335 m³/day)

Percentage Probability Of Exceedance	Predicted Freeze-Up Date	Number of Open-Water Days from July 17 to Freeze Up	Number of Rainfall Days from July 17 to Freeze-Up	Historic Precipitation (mm)			Predicted Historic Surplus (mm)			Predicted Reservoir Deficit at Freeze-Up (m³)	Predicted Available Water Supply at Freeze-Up (m³) [4]	Predicted Reservoir Level at Freeze-Up (masl)
				Open Water Period	August	September	Open Water Period	August	September			
0 (Max)	06-Nov	112	74	283	93 (70)	92 (70)	222	60 (42)	79 (56)	63,849	1,226,677	111.12
5	02-Nov	109	72	248	84 (67)	92 (73)	190	54 (41)	78 (59)	165,005	1,125,521	110.79
10	30-Oct	106	70	213	74 (64)	92 (79)	158	48 (40)	78 (65)	266,161	1,024,365	110.46
25	16-Oct	91	65	184	63 (66)	58 (60)	128	44 (49)	45 (51)	405,755	884,771	110.00
50	14-Oct	89	50	147	58 (61)	45 (48)	83	33 (35)	34 (37)	521,845	768,681	109.61
75	10-Oct	85	41	108	47 (49)	34 (36)	56	18 (23)	24 (30)	624,035	666,491	109.26
90	05-Oct	80	35	95	32 (46)	24 (34)	39	7 (14)	13 (24)	656,835	633,691	109.14
95	04-Oct	79	32	95	31 (46)	22 (33)	37	4 (11)	11 (26)	677,378	613,148	109.06
100 (Min)	03-Oct	78	29	94	30 (30)	20 (20)	35	1 (1)	8 (8)	697,920	592,606	108.99

Notes:
1. Unbracketed precipitation and surplus values are based on independent probability distributions for examined month.
2. Bracketed monthly precipitation and surplus values are normalised based on total precipitation or surplus for the Open Water Period July 17 to Freeze-up
3. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.
4. Predicted Available Water Supply at Freeze-Up calculated by removing 9 months of ice storage (585,000 m³), reservoir deficit (tabulated) and dead storage (80,667 m³) from total reservoir storage capacity (1,956,193 m³).

4.1.3 Predicted Precipitation, Surplus and Reservoir Level under 115,000 m^3/Month Water Consumption Scenario

Table 4 considers the same meteorological data previously discussed for Table 2, but accounts for the additional effects of a daily water consumption rate of 3,850 m^3 (or 115,000 m^3 per month).

Based on the ten year meteorological period considered, it is estimated that the median water supply deficit at a consumption rate of 115,000 m^3 would approximate 565,000 cubic metres. At the extreme ends of annual water balances for the same period, there is a possibility that this water supply deficit could decrease, or increase, to approximately 100,000 or 743,000 cubic metres, respectively.

Golder (2013) has previously inferred a relationship between winter length and the quantity of reservoir water that is converted to ice. Based on this relationship, an average winter length of 8 months was shown to lock up as much as 505,000 m^3 of reservoir water (unavailable until melt) and a longer winter duration of 9 months could lock up as much as 585,000 m^3 of reservoir water. For the purposes of evaluating water supply deficits in a conservative manner, a 9 month winter and equivalent ice storage was selected for this assessment.

Given that up to 585,000 cubic metres of active (accessible) reservoir storage (circa 1,875,500 m^3) may be converted to ice during the winter months (Golder 2013) and assuming an average winter length of 9 months, a 115,000 m^3/month water consumption rate could potentially lead to over-winter water shortages for the 10 through 100 percent probability outcomes presented in Table 4.

Table 4: Precipitation and Predicted Catchment Surplus for 2008 through 2017 Period Under 115,000 m^3/month Water Consumption Scenario (3,850 m^3/day)

Percentage Probability Of Exceedance	Predicted Freeze-Up Date	Number of Open-Water Days from July 17 to Freeze Up	Number of Rainfall Days from July 17 to Freeze-Up	Historic Precipitation (mm)			Predicted Historic Surplus (mm)			Predicted Reservoir Deficit at Freeze-Up (m^3)	Predicted Available Water Supply at Freeze-Up (m^3) [4]	Predicted Reservoir Level at Freeze-Up (masl)
				Open Water Period July 17 to Freeze-Up	August	September	Open Water Period July 17 to Freeze-Up	August	September			
0 (Max)	06-Nov	112	74	283	93 (70)	92 (70)	222	60 (42)	79 (56)	99,872	1,190,654	111.00
5	02-Nov	109	72	248	84 (67)	92 (73)	190	54 (41)	78 (59)	204,744	1,085,782	110.66
10	30-Oct	106	70	213	74 (64)	92 (79)	158	48 (40)	78 (65)	309,615	980,911	110.32
25	16-Oct	91	65	184	63 (66)	58 (60)	128	44 (49)	45 (51)	455,308	835,218	109.83
50	14-Oct	89	50	147	58 (61)	45 (48)	83	33 (35)	34 (37)	564,585	725,941	109.46
75	10-Oct	85	41	108	47 (49)	34 (36)	56	18 (23)	24 (30)	674,230	616,296	109.07
90	05-Oct	80	35	95	32 (46)	24 (34)	39	7 (14)	13 (24)	703,020	587,506	108.97
95	04-Oct	79	32	95	31 (46)	22 (33)	37	4 (11)	11 (26)	722,865	567,661	108.90
100 (Min)	03-Oct	78	29	94	30 (30)	20 (20)	35	1 (1)	8 (8)	742,710	547,816	108.82

Notes:
1. Unbracketed precipitation and surplus values are based on independent probability distributions for examined month.
2. Bracketed monthly precipitation and surplus values are normalised based on total precipitation or surplus for the Open Water Period July 17 to Freeze-up
3. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.
4. Predicted Available Water Supply at Freeze-Up calculated by removing 9 months of ice storage (585,000 m^3), reservoir deficit (tabulated) and dead storage (80,667 m^3) from total reservoir storage capacity (1,956,193 m^3).

4.2 Precipitation and Meteorological Surplus Required to Fill Reservoir

Using the 2008 through 2017 meteorological data referred to in Section 2.2.2 and water level reset function referred to in Section 2.2.3, model simulations were also carried out for the three water consumption scenarios identified in Section 2.2.1 to ascertain the quantity of precipitation that would be required from August 1 to freeze-up in order to replenish the Lake Geraldine reservoir to just below its design level of 111.33 masl. This approach was deemed necessary because insufficient meteorological surpluses in the final few open-water days before freeze-up to offset water consumption were identified in some years, regardless of the increase in precipitation. The following water supply deficits were considered acceptable buffers to establish the necessary increases in precipitation to replenish the reservoir:

- No Water Consumption Scenario – deficit of 10,000 m^3;
- 100,000 m^3/month Water Consumption Scenario – two weeks of consumption equivalent to 46,690 m^3; and
- 115,000 m^3/month Water Consumption Scenario – two weeks of consumption equivalent to 53,900 m^3.

The following sub-sections identify relevant considerations in the interpretation of the amount of precipitation necessary to replenish the reservoir during this open-water period, discuss the approach adopted to consider these considerations and present the results relevant to each of the three water consumption scenarios.

4.2.1 Interpretation of Reservoir Filling Results

In transitioning historic precipitation data to that necessary to replenish the reservoir, the reader should be aware of a number of considerations that are fundamental to adequate interpretation of the results presented in Section 4.2.2 through 4.3.4.

4.2.1.1 Consideration of Sensitivities of Results to Meteorological Regimes

Establishing the amount of precipitation required to replenish the reservoir is complex for a number of reasons.

Firstly, the limiting effects of evapotranspiration and soil and depression storage necessarily imply that the total quantity of precipitation required to fill the reservoir needs to be greater than the reservoir deficit (i.e., soil and depression storage intercept a fraction of incident precipitation across the catchment that does not translate to inflow to the reservoir). Hence, antecedent weather conditions such as the amount and intensity of rainfall, as well as air temperature and wind conditions interceding rainfall, are important determinants to establishing to what extent soil or depression storage is exhausted or needs to fill before generating runoff that can enter the reservoir.

Secondly, this complexity is compounded by the rate of precipitation delivery to the system. The same monthly precipitation amount can yield entirely different quantities of inflow to the reservoir depending on the distribution and intensity of precipitation delivered to ground surface. For example, 100 mm of rainfall uniformly distributed across a month would typically result in lower total monthly runoff volumes than the same quantity off rainfall over a day. In the latter case, evapotranspiration would have insufficient opportunity to affect soil and depression storage volumes in a meaningful way.

Lastly, the duration of the remaining ice-free period (between July 17 and the date of freeze-up) loosely determines the number of rainfall days available to replenish the reservoir. In other words, an early winter would conceivably require higher average daily precipitation amounts than the precipitation amounts required to replenish the reservoir before a late winter.

4.2.1.2 Distribution of Historic and Necessary Precipitation and Surplus Amounts

By supplementing the amount of historic rainfall with that required to replenish the reservoir, the probability distribution of decadal rainfall becomes considerably contracted relative to that for measured conditions. Accordingly, it is important to note that the monthly percent probability values presented in Table 6, 8 and 10 may not be directly compared to the monthly percent probability values in Tables 2, 3 and 4. In rare cases, a small decrease in monthly required precipitation values may be apparent. Accordingly, average monthly precipitation requirements are presented in each sub-section in Tables 5, 7 and 9.

4.2.2 Estimated Necessary Precipitation and Catchment Surplus to Replenish Reservoir by Freeze-Up under No Water Consumption Scenario

Table 5 provides a simplified interpretation of the 2008 through 2017 distribution statistics subsequently presented in Table 6 (overleaf) and presents the average arithmetic precipitation and meteorological surpluses required to replenish the reservoir (to a deficit of 10,000 m^3) from an initial water level of 109.6 masl under the no consumption scenario, for an average ice free period (July 17 to freeze-up). Relative to average annual precipitation amounts measured between 2008 and 2017, average annual precipitation amounts would need to increase by approximately 33% in order to generate the necessary meteorological surplus to replenish the reservoir to a deficit of 10,000 m^3.

Despite featuring less precipitation than in August, the effect of cooling air temperatures on the proportion of precipitation converted to meteorological surplus in September is conspicuous in its effect on the ratio between precipitation and meteorological surplus. In contrast, the lowered ratio in October is likely attributed to a relative increase in ET losses from soil and depression storage.

Table 5: Average (Arithmetic) Precipitation and Meteorological Surplus Required to Replenish Lake Geraldine Reservoir (2008 through 2017) under No Consumption Scenario

Period	Required Precipitation (mm)	Required Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
July 17 to Freeze-Up (Varies) [1]	207	149	72%
July 17 through 31	44	27	69%
August	80	56	78%
September	68	56	92%
October 1 to Freeze-Up (Varies) [1]	15	10	77%
November 1 to Freeze-Up (Varies) [1, 2]	1	1[1]	n/a[2]

Notes:
1. Effective length of ice-free period (i.e., the number of days since July 17 to estimated freeze up day) differs between years.
2. Rounding errors over a short period in 2010 render a comparison of precipitation and meteorological surplus meaningless.

Given the considerations previously presented in Section 4.2.1, the results in Table 6 should be interpreted with a degree of caution while providing the reader with a reasonable understanding of the significant influence of meteorological variability over the 2008 through 2017 period.

The results presented in Table 6 exhibit increased precipitation and meteorological surplus amounts relative to average measured historic conditions (see Table 2).

Precipitation over the July 17 through freeze-up period would need to increase between 18 mm and 131 mm to generate the additional surplus required to full the reservoir to within 10,000 m^3 of its storage capacity.

Table 6: Required Precipitation and Surplus to Replenish Reservoir by Freeze-Up Under No Water Consumption Scenario

Percentage Probability of Exceedance	Predicted Freeze-Up Date	Predicted Reservoir Deficit (m^3)	Predicted Total Surplus Required to Replenish Reservoir (mm)			Predicted Total Precipitation Required to Replenish Reservoir		
			Open Water Period from July 17 to Freeze-Up	August	September	Open Water Period from July 17 to Freeze-Up	August	September
0 (Max)	06-Nov	6,679	140	15 (55)	23 (84)	195	42 (88)	34 (72)
5	02-Nov	7,116	144	18 (57)	24 (77)	197	45 (90)	35 (70)
10	30-Oct	7,554	148	20 (58)	24 (71)	200	48 (93)	35 (68)
25	16-Oct	84,842	150	38 (69)	33 (61)	202	61 (91)	46 (68)
50	14-Oct	245,100	150	56 (60)	58 (63)	206	77 (81)	68 (72)
75	10-Oct	333,950	150	63 (53)	76 (64)	210	86 (74)	89 (77)
90	05-Oct	363,128	151	104 (60)	87 (50)	216	124 (83)	99 (67)
95	04-Oct	385,484	152	104 (52)	88 (44)	221	130 (79)	101 (61)
100	03-Oct	407,840	153	104 (47)	89 (40)	225	137 (76)	103 (58)

Notes:
1. Unbracketed precipitation and surplus values are based on independent probability distributions for examined month.
2. Bracketed monthly precipitation and surplus values are normalised to period total rather than presented as independent distributions.
3. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.

4.2.3 Estimated Necessary Precipitation and Catchment Surplus to Replenish Reservoir by Freeze-Up under 100,000 m^3/Month Water Consumption Scenario

Table 7 provides a simplified interpretation of the 2008 through 2017 distribution statistics subsequently presented in Table 8 (overleaf) and presents the average arithmetic precipitation and meteorological surpluses required to replenish the reservoir (to a two-week consumption deficit) from an initial water level of 109.6 masl under the 100,000 m^3/month consumption scenario, for an average ice free period (July 17 to freeze-up). Relative to average annual precipitation amounts measured between 2008 and 2017, average annual precipitation amounts would need to increase by approximately 87% in order to generate the necessary meteorological surplus to replenish the reservoir to a deficit of 10,000 m^3.

On average (arithmetically), a 41% increase in precipitation relative to the no consumption scenario would be necessary to replenish the reservoir before freeze-up, resulting in a 56% increase in surplus over the July 17 to Freeze-up period relative to historic conditions. The beneficial effects of exhausted soil and depression storage within the catchment are notable when comparing the results in Table 7 with those previously presented in Table 5.

Table 7: Average (Arithmetic) Precipitation and Meteorological Surplus Required to Replenish Lake Geraldine Reservoir (2008 through 2017) under 100,000 m^3/Month Consumption Scenario

Period	Required Precipitation (mm)	Required Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
July 17 to Freeze-Up (Varies)[1]	292	233	80%
July 17 through 31	63	46	73%
August	112	88	79%
September	95	83	87%
October 1 to Freeze-Up (Varies)[1]	21	15	71%
November 1 to Freeze-Up (Varies)[1, 2]	1[2]	1	n/a[2]

Notes:
1. Effective length of ice-free period (i.e., the number of days since July 17 to estimated freeze up day) differs between years.
2. Rounding errors over a short period in 2010 render a comparison of precipitation and meteorological surplus meaningless.

Given the considerations previously presented in Section 4.2.1, the results in Table 8 should be interpreted with a degree of caution while providing the reader with a reasonable understanding of the significant influence of meteorological variability over the 2008 through 2017 period.

The results presented in Table 8 exhibit increased precipitation and meteorological surplus amounts relative to average measured historic conditions (see Table 3).

Precipitation over the July 17 through freeze-up period would need to increase between 18 mm and 242 mm to generate the additional surplus required to full the reservoir to within 46,690 m^3 (equivalent to two weeks water consumption) of its storage capacity.

Table 8: Required Precipitation and Surplus to Replenish Reservoir by Freeze-Up Under 100,000 m^3/month Water Consumption Scenario (3,335 m^3/day)

Percentage Probability of Exceedance	Predicted Freeze-Up Date	Predicted Reservoir Deficit (m^3)	Predicted Total Surplus Required to Replenish Reservoir (mm)			Predicted Total Precipitation Required to Replenish Reservoir		
0 (Max)	06-Nov	63,849	204	41 (100)	36 (86)	262	66 (127)	46 (89)
5	02-Nov	165,005	212	42 (96)	39 (90)	266	68 (126)	50 (92)
10	30-Oct	266,161	220	42 (93)	43 (94)	271	69 (124)	53 (96)
25	16-Oct	405,755	222	59 (98)	54 (89)	276	83 (121)	66 (97)
50	14-Oct	521,845	224	86 (90)	82 (86)	287	106 (111)	92 (97)
75	10-Oct	624,035	236	102 (89)	107 (94)	296	126 (111)	119 (105)
90	05-Oct	656,835	269	148 (102)	128 (88)	332	172 (125)	142 (103)
95	04-Oct	677,378	272	150 (90)	129 (77)	334	176 (114)	142 (92)
100	03-Oct	697,920	275	152 (81)	130 (69)	336	180 (105)	142 (83)

Notes:
1. Unbracketed precipitation and surplus values are based on independent probability distributions for examined open-water period or month.
2. Bracketed monthly precipitation and surplus values are normalised to period total rather than presented as independent distributions.
3. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.

4.2.4 Estimated Necessary Precipitation and Catchment Surplus to Replenish Reservoir by Freeze-Up under 115,000 m^3/Month Water Consumption Scenario

Table 9 provides a simplified interpretation of the 2008 through 2017 distribution statistics subsequently presented in Table 9 (overleaf) and presents the average arithmetic precipitation and meteorological surpluses required to replenish the reservoir (to a two-week consumption deficit) from an initial water level of 109.6 masl under the 115,000 m^3/month consumption scenario, for an average ice free period (July 17 to freeze-up). Relative to average annual precipitation amounts measured between 2008 and 2017, average annual precipitation amounts would need to increase by approximately 97% in order to generate the necessary meteorological surplus to replenish the reservoir to a deficit of 10,000 m^3.

On average (arithmetically), a 49% increase in precipitation relative to the no consumption scenario would be necessary to replenish the reservoir before freeze-up, resulting in a 67% increase in surplus over the July 17 to Freeze-up period relative to historic conditions. The beneficial effects of exhausted soil and depression storage within the catchment are notable when comparing the results in Table 9 with those previously presented in Tables 5 and 7.

Table 9: Average (Arithmetic) Precipitation and Meteorological Surplus Required to Replenish Lake Geraldine Reservoir (2008 through 2017) under 115,000 m^3/Month Consumption Scenario

Period	Precipitation (mm)	Meteorological Surplus (mm)	Percentage of Precipitation Converted to Meteorological Surplus
July 17 to Freeze-Up (Varies)[1]	308	249	81%
July 17 through 31	67	50	75%
August	118	94	80%
September	100	88	88%
October 1 to Freeze-Up (Varies) [1]	23	16	70%
November 1 to Freeze-Up (Varies)[1,2]	1[2]	1	n/a[2]

Notes:
1. Effective length of ice-free period (i.e., the number of days since July 17 to estimated freeze up day) differs between years.
2. Rounding errors over a short period in 2010 render a comparison of precipitation and meteorological surplus meaningless.

Given the considerations previously presented in Section 4.2.1, the results in Table 10 should be interpreted with a degree of caution while providing the reader with a reasonable understanding of the significant influence of meteorological variability over the 2008 through 2017 period.

The results presented in Table 10 exhibit increased precipitation and meteorological surplus amounts relative to average measured historic conditions (see Table 4).

Precipitation over the July 17 through freeze-up period would need to increase between 29 mm and 283 mm to generate the additional surplus required to full the reservoir to within 53900 m^3 (equivalent to two weeks water consumption) of its storage capacity.

Table 10: Required Precipitation and Surplus to Replenish Reservoir by Freeze-Up Under 115,000 m³/month Water Consumption Scenario (3,850 m³/day)

Percentage Probability of Exceedance	Predicted Freeze-Up Date	Predicted Reservoir Deficit (m³)	Predicted Total Surplus Required to Replenish Reservoir (mm)			Predicted Total Precipitation Required to Replenish Reservoir		
0 (Max)	06-Nov	99,872	213	45 (106)	37 (87)	271	72 (135)	48 (90)
5	02-Nov	204,744	222	47 (102)	43 (93)	277	73 (132)	53 (96)
10	30-Oct	309,615	230	49 (100)	48 (98)	283	74 (129)	59 (103)
25	16-Oct	455,308	232	62 (101)	58 (94)	286	86 (126)	70 (102)
50	14-Oct	564,585	235	90 (93)	88 (91)	298	110 (115)	99 (103)
75	10-Oct	674,230	248	115 (98)	111 (94)	307	139 (118)	124 (105)
90	05-Oct	703,020	305	155 (114)	135 (99)	369	179 (138)	148 (114)
95	04-Oct	722,865	310	158 (101)	135 (87)	373	183 (125)	148 (101)
100	03-Oct	742,710	316	160 (91)	136 (77)	377	187 (115)	148 (91)

Notes:
1. Unbracketed precipitation and surplus values are based on independent probability distributions for examined open-water period or month.
2. Bracketed monthly precipitation and surplus values are normalised to period total rather than presented as independent distributions.
3. For conservatism, evaporative losses from the reservoir are assumed to occur at the maximum water level of 111.33 masl with a calculated surface area of 29 ha. This rate will decline with reduced water levels.

4.3 Characteristic Monthly Precipitation Rates and Meteorological Surplus

Tables 11 and 12 present characteristic monthly precipitation and the predicted delivery of meteorological surpluses to the Lake Geraldine reservoir on a monthly basis.

As expected, the bulk of meteorological surplus delivery to the Lake Geraldine reservoir occurs in the month of June coinciding with the predicted melt of snow accumulation throughout the watershed. The melt is succeeded by the two wettest open-water months with the amount of precipitation subsequently declining through September and October. It should be noted that during one-year (2009) evapotranspiration losses from the catchment and Lake Geraldine outstrip the amount of precipitation runoff delivered to the system. Based on the 2008 through 2017 period examined, the highest monthly precipitation rate occurs during the month of November. The model predicts a limited quantity of wet precipitation that is assumed to result in runoff during the same month. Snowmelt throughout the winter is predicted to be minimal, however a significant proportion of accumulated snow is lost to sublimation

Table 11: Characteristic Historic Monthly Meteorological Surplus Distributions to the Lake Geraldine Reservoir (2008 through 2017)

Percentage Probability of Exceedance	Annual Total (mm)	January (mm)	February (mm)	March (mm)	April (mm)	May (mm)	June (mm)	July (mm)	August (mm)	September (mm)	October (mm)	November (mm)	December (mm)
0 (Max)	568	11 (7)	0 (0)	0 (0)	15 (10)	69 (46)	390 (262)	156 (105)	60 (40)	79 (53)	26 (17)	31 (21)	9 (6)
5	506	7 (5)	0 (0)	0 (0)	8 (6)	64 (49)	283 (217)	114 (87)	54 (42)	78 (60)	25 (19)	20 (16)	7 (5)
10	445	2 (2)	0 (0)	0 (0)	1 (1)	60 (56)	176 (165)	72 (67)	48 (45)	78 (73)	24 (22)	10 (9)	4 (4)
25	247	0 (0)	0 (0)	0 (0)	0 (0)	53 (41)	124 (95)	30 (23)	44 (33)	45 (35)	22 (17)	4 (3)	0 (0)
50	226	0 (0)	0 (0)	0 (0)	0 (0)	20 (25)	59 (73)	23 (29)	33 (41)	34 (42)	12 (15)	0 (0)	0 (0)
75	189	0 (0)	0 (0)	0 (0)	0 (0)	10 (17)	38 (66)	14 (23)	18 (30)	24 (41)	7 (12)	0 (0)	0 (0)
90	170	0 (0)	0 (0)	0 (0)	0 (0)	7 (20)	21 (59)	10 (27)	7 (20)	13 (35)	3 (8)	0 (0)	0 (0)
95	123	0 (0)	0 (0)	0 (0)	0 (0)	4 (11)	15 (45)	4 (13)	4 (14)	11 (33)	2 (7)	0 (0)	0 (0)
100	75	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	8 (33)	-1 (-6)	1 (6)	9 (36)	1 (6)	0 (0)	0 (0)

Table 12: Characteristic Historic Monthly Precipitation Distributions (2008 through 2017)

Percentage Probability of Exceedance	Annual Total (mm)	January (mm)	February (mm)	March (mm)	April (mm)	May (mm)	June (mm)	July (mm)	August (mm)	September (mm)	October (mm)	November (mm)	December (mm)
0 (Max)	669	71 (47)	142 (94)	131 (87)	80 (53)	39 (26)	79 (52)	189 (126)	93 (62)	93 (62)	38 (25)	33 (22)	18 (12)
5	622	51 (39)	100 (76)	101 (77)	59 (45)	34 (26)	72 (55)	143 (108)	84 (63)	92 (70)	36 (27)	30 (23)	18 (14)
10	575	31 (28)	58 (53)	70 (64)	39 (35)	28 (26)	65 (59)	96 (87)	74 (67)	92 (83)	34 (31)	27 (24)	18 (16)
25	393	17 (16)	33 (29)	47 (42)	28 (25)	26 (24)	47 (42)	67 (60)	63 (57)	58 (51)	27 (24)	13 (12)	13 (12)
50	359	11 (12)	16 (17)	23 (25)	17 (18)	24 (26)	38 (41)	57 (62)	56 (60)	45 (49)	24 (26)	11 (12)	11 (12)
75	341	7 (9)	10 (14)	13 (19)	11 (16)	15 (21)	27 (38)	45 (64)	47 (67)	34 (49)	14 (20)	8 (11)	8 (12)
90	301	3 (5)	6 (11)	11 (19)	10 (16)	12 (20)	23 (39)	37 (62)	32 (54)	24 (40)	9 (15)	6 (10)	6 (10)
95	254	2 (4)	6 (9)	10 (16)	10 (15)	12 (19)	22 (36)	28 (45)	31 (50)	22 (35)	6 (10)	5 (9)	4 (7)
100	208	2 (2)	5 (7)	9 (13)	9 (14)	12 (18)	21 (32)	19 (29)	30 (45)	20 (31)	4 (5)	5 (7)	2 (4)

5.0 CONCLUSIONS

Based on the preceding discussion of results and previously noted assumptions and limitations the following conclusions are summarised:

1) The open-water period available for replenishment of the reservoir (July 17 to predicted freeze-up) ranges from 80 to 112 days (predicted freeze-up dates range between October 5 and November 6).

2) The assessment of recent meteorological conditions (2008 to 2017) suggests that, on average, 63% of the measured precipitation falling between July 17 and predicted freeze-up results in meteorological surpluses that enter the Lake Geraldine reservoir. Given the paucity of meteorological surpluses in the final days before freeze-up for some of these years, however, reservoir losses attributed to evapotranspiration and water consumption mean the reservoir cannot always be filled to its entirety. In order to establish a target water reservoir level for freeze-up, the following permissible deficits were selected:

    a. A 10,000 m^3 storage deficit was selected as appropriate for the no water consumption scenario;

    b. Storage deficits equivalent to two weeks of water consumption were selected for the 100,000 m^3/month (46,690 m^3) and 115,000 m^3/month (53,900 m^3) water consumption scenarios.

3) For the three consumption rates evaluated, the predicted water supply deficit ranges as follows:

    a. The no water consumption scenario incurs a water supply deficit between 7,000 m^3 and 408,000 m^3, with a 50th percentile of 245,000 m^3;

    b. The 100,000 m^3/month water consumption scenario incurs a water supply deficit between 64,000 m^3 and 698,000 m^3, with a 50th percentile of 522,000 m^3; and

    c. The 115,000 m^3/month water consumption scenario incurs a water supply deficit between 100,000 m^3 and 743,000 m^3, with a 50th percentile of 565,000 m^3.

4) The assessment of meteorological surpluses for the July 17 to freeze-up period indicates that, relative to the measured 2008 through 2017 arithmetic average precipitation amount (156 mm), arithmetic average precipitation amounts required to achieve close to maximum water supplies by freeze-up would need to increase to:

    a. 207 mm for the no water consumption scenario;

    b. 292 mm for the 100,000 m^3/month water consumption scenario; and

    c. 308 mm for the 115,000 m^3/month water consumption scenario.

6.0 CLOSURE

We trust that the information provide din this technical memorandum meets your immediate needs and appreciate the opportunity to contribute to your interesting work. Please contact the undersigned if you have any questions or concerns regarding any of the content documented in this technical memorandum.

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